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# Bivariate analysis of floods in climate impact assessments

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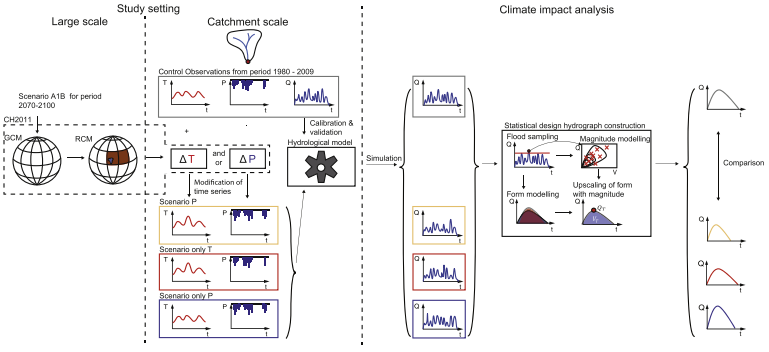
## HIGHLIGHTS

- Design hydrograph construction is useful for climate change impact studies.
- Peak discharges and hydrograph volumes are jointly but not proportionally affected by climate change.
- The construction of seasonal design hydrographs is more informative in climate impact studies than the construction of annual design hydrographs.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Climate impact studies regarding floods usually focus on peak discharges and a bivariate assessment of peak discharges and hydrograph volumes is not commonly included. A joint consideration of peak discharges and hydrograph volumes, however, is crucial when assessing flood risks for current and future climate conditions. Here, we present a methodology to develop synthetic design hydrographs for future climate conditions that jointly consider peak discharges and hydrograph volumes. First, change factors are derived based on a regional climate model and are applied to observed precipitation and temperature time series. Second, the modified time series are fed into a calibrated hydrological model to simulate runoff time series for future conditions. Third, these time series are used to construct synthetic design hydrographs. The bivariate flood frequency analysis used in the construction of synthetic design hydrographs takes into account the dependence between peak discharges and hydrograph volumes, and represents the shape of the hydrograph. The latter is modeled using a probability density function while the dependence between the design variables peak discharge and hydrograph volume is modeled using a copula. We applied this approach to a set of eight mountainous catchments in Switzerland to construct catchment-specific and season-specific design hydrographs for a control and three scenario climates. Our work demonstrates that projected climate changes have an impact not only on peak discharges but also on hydrograph volumes and on hydrograph shapes both at an annual and at a seasonal scale. These changes are not necessarily proportional which implies that climate impact assessments on future floods should consider more flood characteristics than just flood peaks.

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## 1. Introduction

Climate change is expected to affect the mean climate and weather extremes both in terms of temperature and precipitation

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(Frei et al., 1998; Scherrer et al., 2016). Changes in climatic conditions strongly affect river runoff generation, snow accumulation and melt, glacier melt, and evapotranspiration (Dobler et al., 2012; Fischer et al., 2015; Horton, 2005) and therefore flood magnitudes (Hall et al., 2014; Kundzewicz, 2002) and their seasonality (Blöschl et al., 2017; Köplin et al., 2014; Pilling and Jones, 2002). Both the magnitude and frequency of flood events are projected to increase under climate change even though observed peak river flows do not yet show clearly detectable trends (Kundzewicz, 2002; Wilby et al., 2008). Such anticipated changes are often not considered in existing design procedures of hydraulic structures such as embankments, dams, or reservoirs (Kundzewicz, 2002).

There is a clear need to have reliable flood frequency estimates with and without climate change to solve flood management tasks (Cameron et al., 2000). Most of the methods exploring the potential impacts of climate change on flood frequency use distributions with parameters that are dependent on time, hydrological variables, or climatological variables (Šraj et al., 2016). Alternative methods involve the analysis of runoff time series simulated via a hydrological model driven by projected meteorological time series (Cameron, 2006; Wilby et al., 2008). The majority of the studies assessing the impact of climate change on floods and flood frequency primarily focus on flood peaks (Cameron, 2006; Hall et al., 2014; Madsen et al., 2014). The hydrograph volume and the hydrograph shape of a flood event are usually not explicitly considered in climate impact assessments on floods even though these aspects might also be affected by climate change. The estimation of hydrograph volumes and the hydrograph shape is indeed important for flood management tasks such as the construction of flood retention basins or drawing hazard maps (Deutsche Vereinigung für Wasserwirtschaft Abwasser und Abfalt, 2012; Klein et al., 2010; Schumann et al., 2010; Tung and Yen, 2005). The volume is required to estimate a sensible dimension of hydraulic structures and to define inundation areas which are used for drawing hazard maps. Thus, these aspects should be taken into account in climate impact studies.

In this study, we propose an evaluation approach for the joint assessment of the impact of climate change on peak discharges, hydrograph volumes, and shapes. The approach is based on the usual approach used in climate impact studies, i.e., it uses a model chain consisting of a global and a regional climate model whose output is fed into a hydrological model to simulate runoff time series. Instead of using these simulated series for a classical univariate frequency analysis, we use them in a bivariate analysis to construct synthetic design hydrographs (SDHs) as proposed by Brunner et al. (2017b). Design flood hydrographs are hydrographs of a suitable probability and magnitude adopted to ensure the safety of hydraulic structures (Xiao et al., 2009), such as dam spillways, bridges, road culverts, levees, or retention basins. SDHs, representing the future flood behavior of a catchment in an aggregated way, are then compared to SDHs constructed for current climate conditions (i.e., based on observed data). The difference with respect to most existing impact studies is that we look at flood volumes and hydrograph shapes in addition to flood peaks. The application of this evaluation approach allows us to address the following research questions:

1. Are peak discharges and hydrograph volumes affected in the same way by projected climate changes (i.e., are their relative changes similar)?
2. Will the SDH shapes change under climate change?

Due to large uncertainties of future precipitation and temperature projections and to a lower extent of the hydrological model and its parameterization, a quantitative assessment of climate changes is highly uncertain at the current stage. Simulations via regional climate models are still challenging to be used in hydrological climate impact studies with regard to hydrological extremes. The delta change approach used in this study also has its limitations when estimating changes in extremes, but was chosen here for simplicity. Despite all limitations and uncertainties, this approach allows us to demonstrate that climate impact assessments on floods should not only focus on peak discharges but should also consider possible impacts on hydrograph volumes and the dependence between peak discharges and hydrograph volumes, as well as on hydrograph shapes.

## 2. Data

The bivariate flood impact assessment approach is illustrated based on eight study catchments in Switzerland (Table 1 and Fig. 1), which belong to the two climatic regions of northeastern Switzerland (CHNE) and western Switzerland (CHW) (CH2011, 2011). These catchments are small to medium-size (45 to 477 km$^2$), situated between 660 and 1360 m.a.s.l., and have an insignificant areal ratio of glaciers ($\leq$0.1%). Their runoff is neither altered by regulated lakes upstream or inland canals nor by urbanized areas. In the Swiss Alps and Pre-Alps, major floods mainly occur in summer due to convective rainfall events, partly in connection with snowmelt. In the Swiss lowlands, major floods occur in all seasons because of the decreasing proportion of snowfall compared to catchments at higher elevations. The study catchments are located either in the lowlands, the Pre-Alps, or the transition zone between the two. The elevation of the 0° line has a decisive influence on the characteristics of floods (Weingartner et al., 2003).

### 2.1. Precipitation and temperature

Hourly precipitation and temperature records were obtained from ground gauging stations of the automatic monitoring network of MeteoSwiss (SwissMetNet) (Federal Office of Meteorology and Climatology MeteoSwiss, 2003) which provide accurate precipitation information, but only at the point of measurement (Sikorska and Seibert, 2016). Areal precipitation and temperature series were computed using the Thiessen polygons approach (Schumann, 1998). To account for elevation differences between stations, a constant correction of 0.6 °C per increase of 100 m was applied to temperature records from individual stations. The elevation correction for precipitation was undertaken directly in the hydrological model.

### 2.2. Runoff

Hourly runoff time series were provided by the Federal Office for the Environment (FOEN). In total, roughly 20 years of observed runoff data were available for the calibration and validation of the hydrological model (years 1990–2010).

## 3. Methods

The evaluation approach to assess the impact of climate change on bivariate design flood estimation represents a model chain which

**Table 1**
Characteristics of the eight study catchments: catchment area [km$^2$], mean catchment elevation [m.a.s.l.], elevation at catchment outlet [m.a.s.l.], and climatic region (northeastern Switzerland (CHNE) or western Switzerland (CHW)).

| River | Gauging station | Area [km$^2$] | Mean elevation [m.a.s.l.] | Station elevation [m.a.s.l.] | Climatic region |
|---|---|---|---|---|---|
| Kleine Emme | Littau | 477 | 1050 | 431 | CHNE |
| Wigger | Zofingen | 368 | 660 | 426 | CHNE |
| Dünnern | Olten | 196 | 750 | 400 | CHNE |
| Muota | Ingenbohl | 316 | 1360 | 438 | CHNE |
| Mentue | Ivonand | 105 | 679 | 449 | CHW |
| Broye | Payerne | 329 | 710 | 441 | CHW |
| Gürbe | Belp | 117 | 837 | 511 | CHW |
| Sionge | Vuippens | 45 | 862 | 681 | CHW |

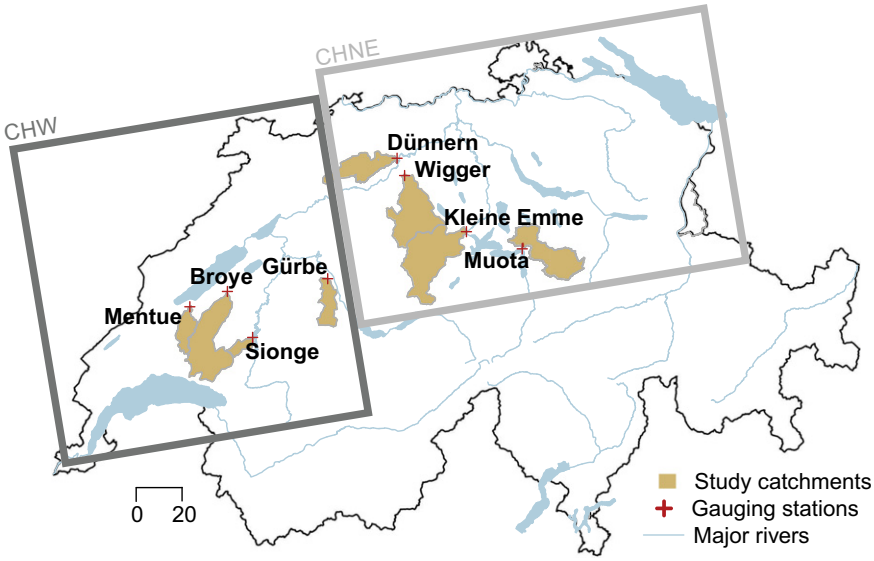


**Fig. 1.** Map of the eight study catchments: Kleine Emme-Littau, Wigger-Zofingen, Dünnern-Olten and Muota-Ingenbohl in the climatic region northeastern Switzerland (CHNE), and Mentue-Yvonand, Broye-Payerne, Gürbe-Belp, and Sionge-Vuippens in the region western Switzerland (CHW).

consists of the following components: a global circulation model (GCM), a regional climate model (RCM), a hydrological model, and a statistical flood frequency model (Fig. 2). Change factors derived from a GCM-RCM chain were used to modify climate time series of temperature and precipitation. These modified time series were fed into a hydrological model that had been calibrated based on observed meteorological and runoff data, representing current climate conditions. The simulated runoff time series were then used to construct design hydrographs. The resulting design hydrographs are characterized by peak discharge, hydrograph volume, and a hydrograph shape. The design hydrographs obtained for the control (current climate) and scenario runs (possible future climate) were finally compared to assess the climate impact in terms of the design variables peak discharge and hydrograph volume. The six steps of the evaluation approach are described in more detail in the following paragraphs:

1. *Selection of climate scenarios:* We defined the period of 1980–2009 as the reference period which represents current climate conditions (CH2011, 2011). The scenario period 2070–2100 was chosen to represent the future climate conditions since changes are expected to be most expressed at the end of the century. To illustrate the approach proposed in this study, we used the A1B emission scenario that assumes increases in greenhouse gas emissions (CH2011, 2011). The A1B emission scenario from the Special Report on Emissions Scenarios (SRES) (IPCC Working group III, 2000) leads to a global mean temperature increase in the range of 2.8–4.2 °C, which approximates the representative

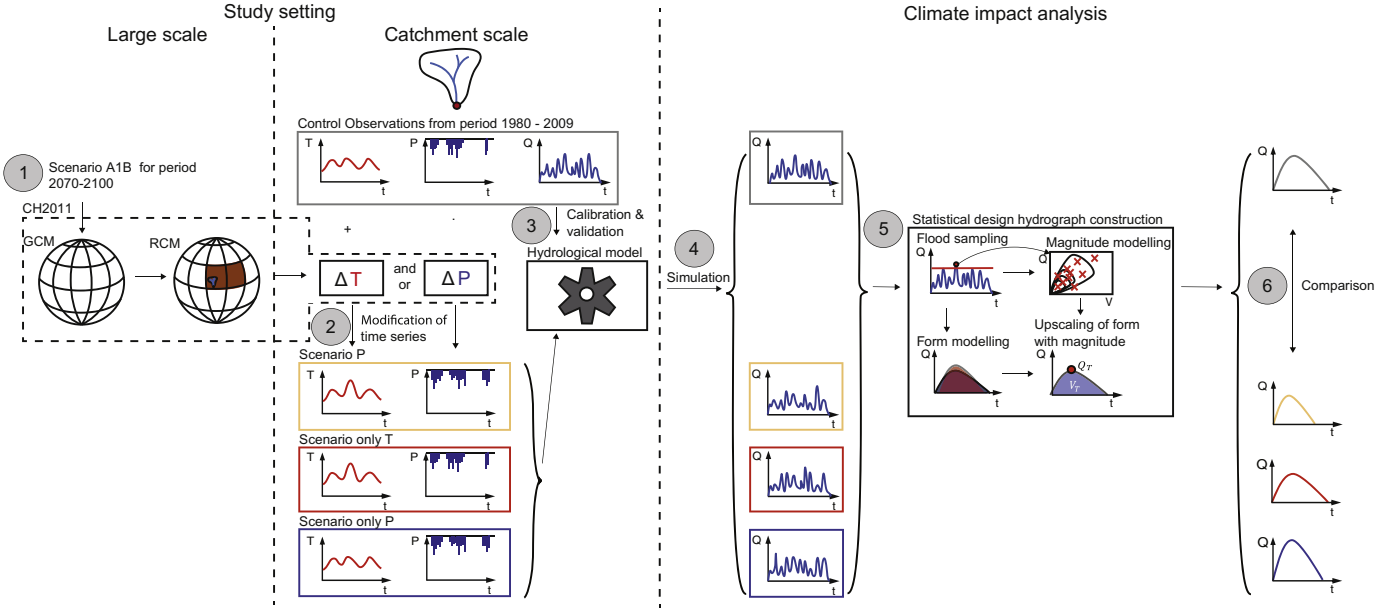


**Fig. 2.** Bivariate climate impact assessment approach. 1) Selection of climate scenario, 2) Derivation of meteorological time series for future climate conditions using the change factor approach, 3) Calibration of a hydrological model, 4) Simulation of runoff time series, 5) Construction of SDHs, 6) Comparison of scenario SDHs to control SDH.

concentration pathway (RCP) 6 and lies between RCP4.5 and RCP8.5, the scenarios developed for IPCC's fifth assessment report (Rogelj et al., 2012).

2. *Derivation of meteorological time series for future climate conditions using the change factor approach:* We used the change factor approach (Hay et al., 2000) to derive meteorological time series that represent future climate conditions under the chosen emission scenario. Daily change factors are available for different climatic regions in Switzerland (CH2011, 2011) and can be obtained from the Center for Climate Systems Modeling (C2SM). The daily change factors are available as lower, medium, and upper estimates relative to the reference period 1980–2009. They were derived based on mean seasonal changes of data derived from a set of GCM-RCM model chains from the ENSEMBLES project (van der Linden et al., 2009) that have been interpolated to daily resolution (Bosshard et al., 2011; CH2011, 2011; Fischer et al., 2012). A complete list of these model chains can be found in Bosshard et al. (2011) Table 1 p. 2778. Expected future temperature series for the scenario period were obtained by adding the temperature change factors to the observed time series in the reference period while the future precipitation series were obtained by multiplying the precipitation change factors for the corresponding days of the year with the observed time series in the reference period (CH2011, 2011). The change factor approach was chosen, instead of working directly with GCM or RCM outputs, because GCMs and RCMs do not properly resolve extreme precipitation events, which are crucial for the triggering of flood events (Dobler et al., 2012; Wilby et al., 2008). The change factor approach allows for the consideration of changes in mean precipitation, which are well represented by RCMs, but retains the observed rainfall patterns instead of using simulated patterns that are associated with large uncertainties. However, the change factor approach might not correctly reflect the expected changes in extreme precipitation or temperature (OCCR et al., 2014). The change factors for precipitation and temperature were used to modify the meteorological time series according to three *scenarios*.

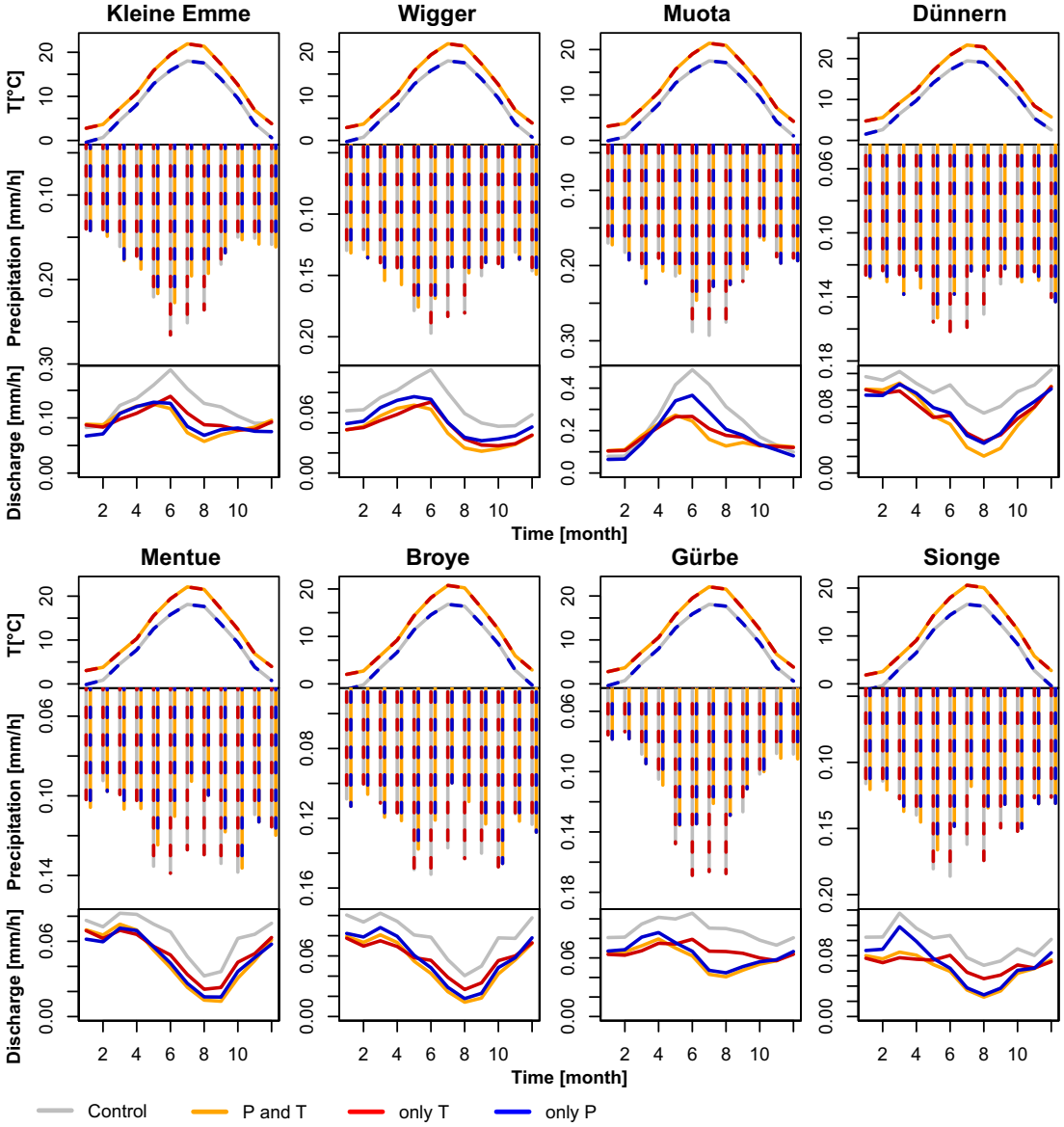


**Fig. 3.** Seasonal cycles of temperature [°C], precipitation [mm/h], and runoff [mm/h] for the eight study catchments belonging to the climatic regions CHNE (upper panel) and CHW (lower panel). Seasonal cycles are given for the control (i.e., using the observed data) and scenario runs. Some scenarios resulted in equivalent temperature and precipitation data which were therefore plotted as dashed instead of bold lines.

The considered scenarios were: I) variation of precipitation and temperature (*P* and *T*), II) variation of temperature (only *T*), and III) variation of precipitation (only *P*) (Fig. 3 upper panels). The choice of these three scenarios allows for a separate assessment of the sensitivity towards temperature and precipitation changes as well as their combined, but not necessarily linear, effect (scenario *P* and *T*).

3. *Calibration of the hydrological model:* Runoff at the catchment outlet was simulated for current and future climate conditions using the semi-distributed hydrological HBV model (Bergström, 1976; Lindström et al., 1997) in the version HBV light (Seibert and Vis, 2012). HBV is a bucket-type model and consists of four routines that account for dynamics of snow, soil moisture, groundwater, and runoff routing. This model has been frequently used for climate change impact studies (e.g. Cloke et al. (2013), Smith et al. (2014), Vormoor et al. (2015)). Input variables are precipitation and temperature, in our case, at an hourly resolution, long term means of evapotranspiration, and daily temperature. The HBV model has 15 parameters that need to be inferred by calibration. A period of 15 years, i.e., 1990–2005 was chosen for model calibration, while the period 2006–2010 was used for model validation. The model was calibrated using a genetic algorithm and Powell optimization (GAP (Seibert, 2000)) by means of a multi-objective calibration using the Kling-Gupta efficiency (Gupta et al., 2009), peak efficiency (Seibert, 2003), and logarithmic efficiency of discharge (Vis et al., 2015) as objective functions. The weights to these objective functions were defined during pre-calibration runs and assigned as 0.3, 0.5, and 0.2 respectively. To represent the uncertainty in model parameters, the model was

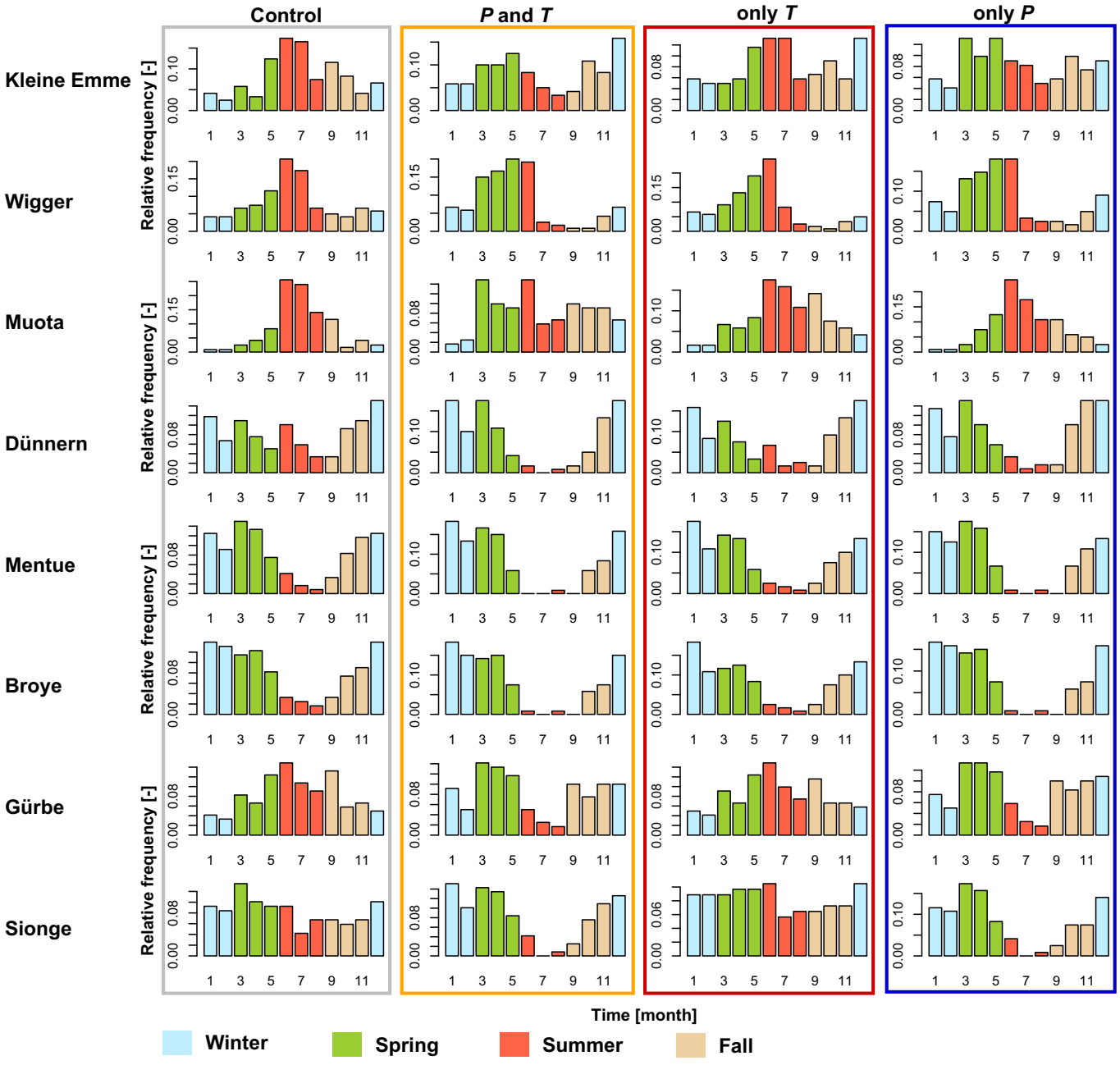


**Fig. 4.** Relative frequency of flood occurrence per month (1: January–12: December) for the eight study catchments sorted by climatic region (Kleine Emme-Dünnern: CHNE, Mentue-Sionge: CHW). The relative frequencies are given for the control (grey), the *P* and *T* (orange), the only *T* (red), and the only *P* (blue) scenarios.

calibrated 100 times resulting in 100 calibrated parameter sets. The achieved average weighted objective functions were 0.70 in the calibration and 0.62 in the validation period. Our initial analysis showed that the choice of one parameter set (out of 100 retained sets) had only a small impact on simulation results when using different climate scenarios. For further analyses, we therefore selected the set which gave the highest value for the weighted objective function.

4. *Simulation of runoff time series:* The calibrated HBV model was used to simulate runoff time series under current climate (reference period 1980–2009), which was used as a control time series, and the three scenario time series (*P* and *T*, only *T*, and only *P*) for the selected future period 2070–2100 (Fig. 3 lower panel). The changes in precipitation and temperature affect the seasonal cycle of runoff, which is projected to generally decrease due to decreased water availability. This decrease is most expressed in the summer months, where precipitation decreases, and is generally small in the winter months, where precipitation slightly increases.
5. *Construction of synthetic design hydrographs:* The four simulated runoff time series (one control and three scenario series) were used for a bivariate flood frequency analysis and the construction of design hydrographs, which provide information of the magnitude of an event with a predefined recurrence interval. We used the statistical model proposed by Brunner et al. (2017b) to construct synthetic design hydrographs based on peak-over-threshold flood samples derived from the control and scenario series. Such SDHs describe a design event in terms of the two dependent design variable quantiles peak discharge and hydrograph volume while considering the shape of the hydrograph. The SDH construction approach can be summarized by three main steps:

(a) Modeling of the hydrograph shape by fitting a probability density function (PDF) to the median hydrograph. Bhunya et al. (2007) showed that PDFs are more suitable to derive unit hydrographs than traditional methods because the area under the curve is guaranteed to be equal to one and can therefore be used as the basis for a design flood hydrograph. Furthermore, probability density functions are quite flexible and can take various shapes. They were fitted to a normalized representative hydrograph shape which was assumed to be the median hydrograph in a catchment.
(b) Estimation of the event magnitude in a bivariate flood frequency analysis considering the dependence between peak discharges and hydrograph volumes using a copula model.
(c) Construction of an SDH by rescaling the form with the magnitude.

For a more detailed description of the construction procedure, we refer the reader to Brunner et al. (2017b).

The approach proposed by Brunner et al. (2017b) is not only suitable for the construction of SDHs under current climate

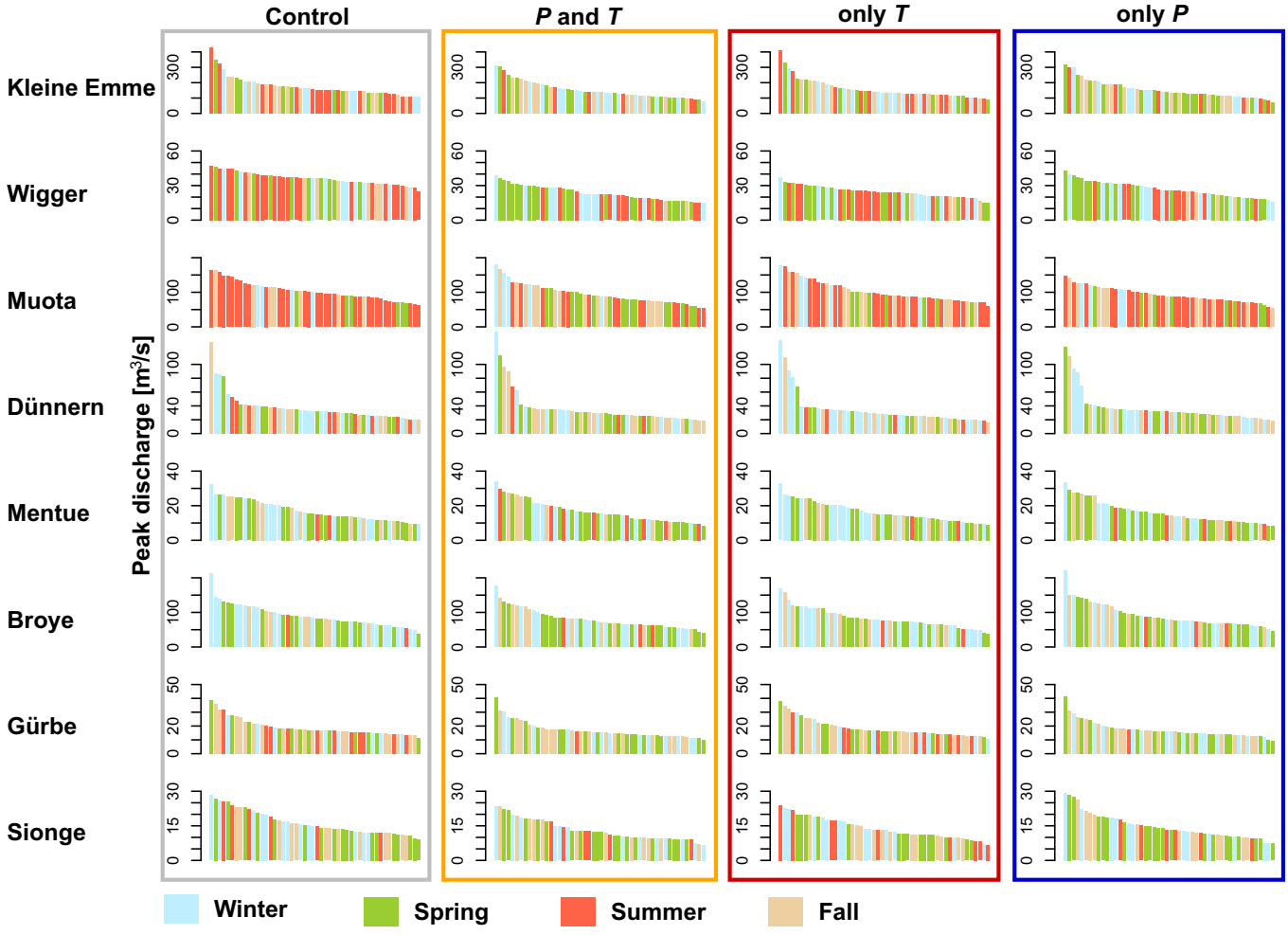


**Fig. 5.** 50 largest events in the eight study catchments (Kleine Emme-Dünnern: CHNE, Mentue-Sionge: CHW) ranked according to their peak discharges [$m^3/s$] and colored according to their season of occurrence. The ranking is provided for the control (grey), the *P* and *T* (orange), the only *T* (red), and the only *P* (blue) scenarios. Changes in the seasonal distribution are indicated by a change in the color pattern.

(control) but can also be applied under changed climate conditions (scenarios). The assumptions underlying the flood frequency model are still valid when using simulated runoff data instead of observed runoff data. The marginal distribution of peak discharges and hydrograph volumes can still be well described by a generalized extreme value (GEV) distribution according to the Kolmogorov–Smirnov goodness-of-fit test. The Joe copula is still a suitable model for modeling the dependence between peak discharges and hydrograph volumes, which is shown by the bootstrap goodness-of-fit test proposed by Genest et al. (2009). The choice of the copula model is rather catchment than scenario dependent. However, the strength of dependence between the two variables slightly changes and, depending on the catchment and the scenario, it can become stronger or weaker compared to the dependence obtained for the control period. This is also valid for the tail dependence (i.e. amount of dependence in the upper-right-quadrant tail or lower-left-quadrant tail of a bivariate distribution), where the tail dependence coefficients (Poulin et al., 2007) do not show a distinct pattern for the different scenarios and catchments. Finally, the lognormal PDF is still suitable to model the shape of the hydrographs according to the Nash–Sutcliffe and Kling–Gupta efficiencies (Gupta et al., 2009). The fulfillment of the aforementioned assumptions allow the construction of SDHs for future scenarios as they are considered here.

In addition to SDHs constructed on an annual basis (using the whole flood sample), we extended our analysis to the construction of season-specific SDHs, which is based on floods occurring in one season. A season-specific construction of SDHs allows for the identification of seasons where changes are expected to have the largest impact on design hydrograph construction, which is of particular importance for climate impact studies. Seasonal SDHs were computed only for seasons with more than five observations since parameter estimation using only a few observations is not robust.

6. *Comparison of scenario SDHs with the control SDH:* The three scenario SDHs were compared to the control SDH to assess the impact of climate change on design flood estimates. Such a comparison allows for an assessment of changes in peak discharges but also of changes in hydrograph volumes and shapes. The comparison was also done for the seasonal SDHs to identify seasons that are the most/least affected by climate change.

## 4. Results

### 4.1. Seasonality of flood events

Flood occurrence was generally projected to shift from summer to spring and/or winter based on the available climate scenarios

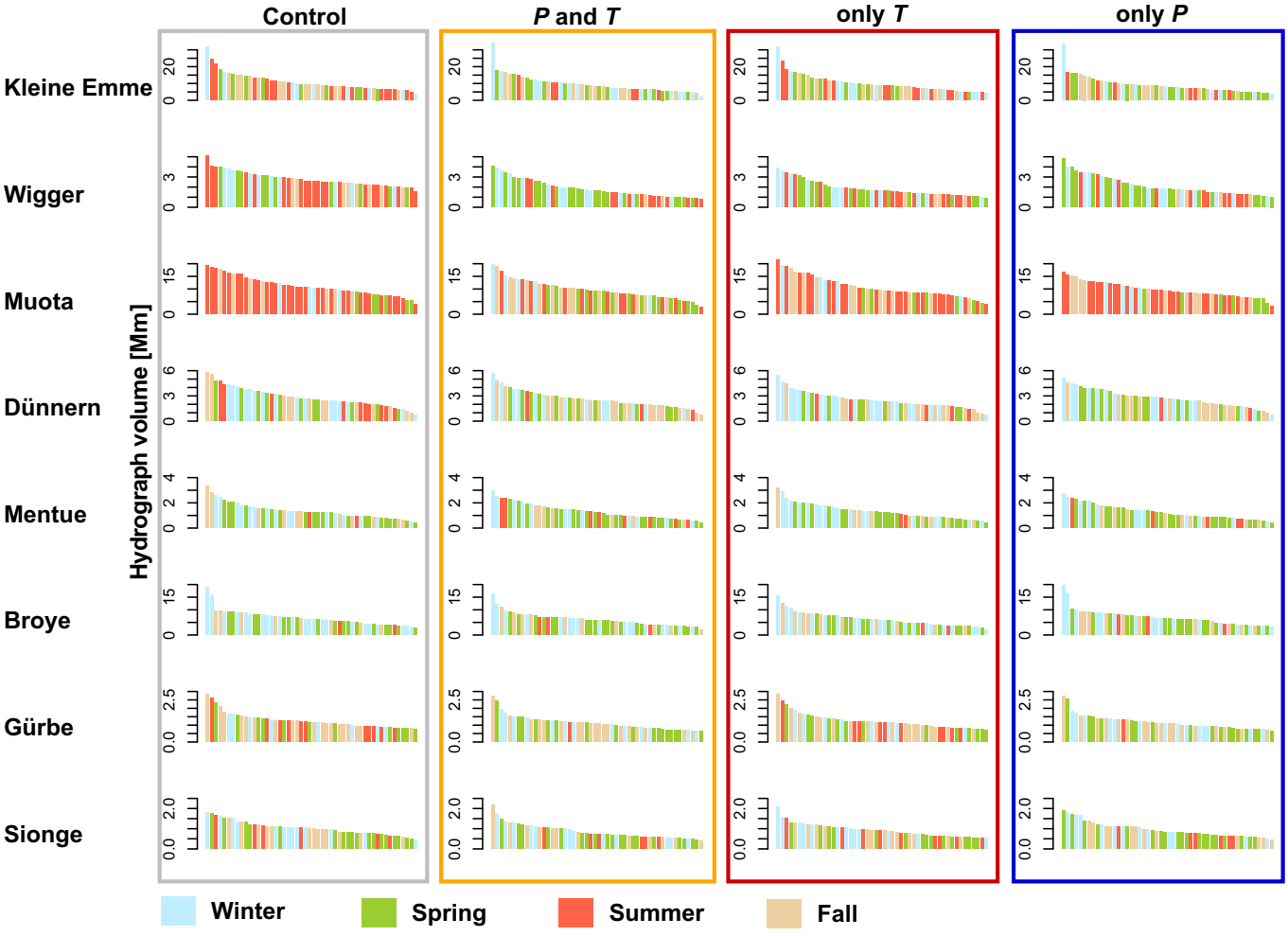


**Fig. 6.** 50 largest events in the eight study catchments (Kleine Emme-Dünnern: CHNE, Mentue-Sionge: CHW) ranked according to their hydrograph volumes [$Mm^3$] and colored according to their season of occurrence. The ranking is provided for the control (grey), the *P* and *T* (orange), the only *T* (red), and the only *P* (blue) scenarios. Changes in the seasonal distribution are indicated by a change in the color pattern.

(see Fig. 4). Catchments with frequent summer floods under current climate were projected to be characterized by more frequent spring and autumn floods, while catchments that showed few summer floods under current climate were projected to experience more frequent spring and winter floods. This seasonal shift was the result of the joint influence of precipitation and temperature changes and was much smaller when only one of the two variables changed. The seasonality did not only change for mean flood occurrence but also for the most extreme events in terms of peak discharges (Fig. 5) and hydrograph volumes (Fig. 6). Please note that a change in the seasonal distribution is indicated by a changing color pattern in Figs. 5 and 6. The occurrence of the extreme events in terms of peak discharges was simulated to shift from summer to spring or winter in the catchments lying in the climatic region of northeastern Switzerland while catchments in the western region were still largely dominated by spring, winter, and fall floods. The magnitude of peak discharges generally seemed to stay stable or to slightly decrease. The season of occurrence of the largest events in terms of hydrograph volumes generally shifted towards winter but also the fall season gained in importance. Unlike peak discharges, flood volumes did not necessarily decrease due to changes in precipitation and temperature.

### 4.2. Design hydrograph construction

Design hydrographs for a return period of 100 years were affected by projected changes in temperature and precipitation (Fig. 7). Both the peak discharge and hydrograph volume of an SDH were affected by a joint change in temperature and precipitation (scenario *P* and *T*). However, they were only weakly affected if only temperature changed (scenario only *T*). The magnitude of the design event in terms of peak discharge and hydrograph volume could increase or decrease depending on the catchment and the climate scenario under consideration, which indicated that these results are highly uncertain. In addition to event magnitude, design hydrograph shapes also slightly changed.

An increase or decrease in peak discharge usually also meant an increase or decrease in hydrograph volumes. However, they did not change proportionally (Fig. 8). The proportions between changes in peak discharges and hydrograph volumes were again catchment and scenario dependent. Points lying on the diagonal line represented proportional changes while points lying off the diagonal line represented disproportional changes. The Dünnern catchment for example showed only weak changes in hydrograph volumes while changes in peak discharges were quite large. On the contrary, the Wigger catchment showed larger changes in hydrograph volumes than in peak discharges. The changes of $Q_T$ and $V_T$ were proportional for most scenarios in the three catchments Muota, Mentue, and Sionge (i.e., most points lay on the diagonal line). The changes of $Q_T$ and $V_T$ were disproportional for most scenarios in the remaining catchments (i.e., points did not lie on diagonal line). Even if the change of hydrograph volume was proportional to the change of peak discharge, these proportions were catchment dependent. The disproportional change in hydrograph volume and peak discharge was even more pronounced when looking at seasonal design variable quantiles for $T = 100$ (Fig. 9). The seasonal proportions were also catchment dependent. There were catchments with rather large volume changes compared to changes in peak discharges in summer or fall than in winter and spring (e.g. Kleine Emme, Sionge). In contrast, there were catchments where the hydrograph volume changed more

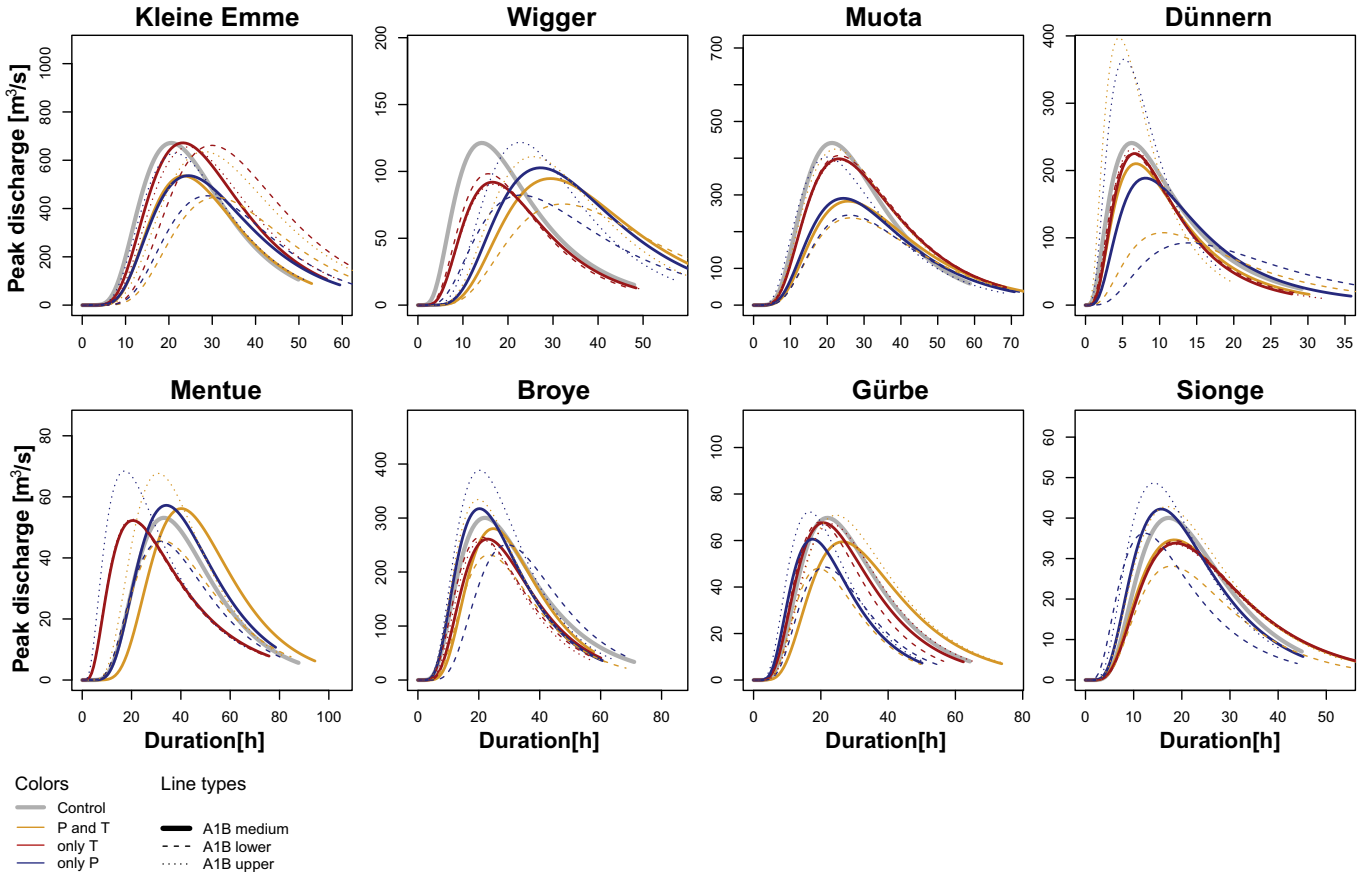


**Fig. 7.** Synthetic design hydrographs for a return period of 100 years for the eight study catchments in the regions CHNE (upper panel) and CHW (lower panel). Design hydrographs are displayed for the control (grey), the *P* and *T* (orange), the only *T* (red), and the only *P* (blue) scenarios. The scenarios refer to the emission scenario A1B lower (dashed lines), medium (solid line), and upper (pointed line).

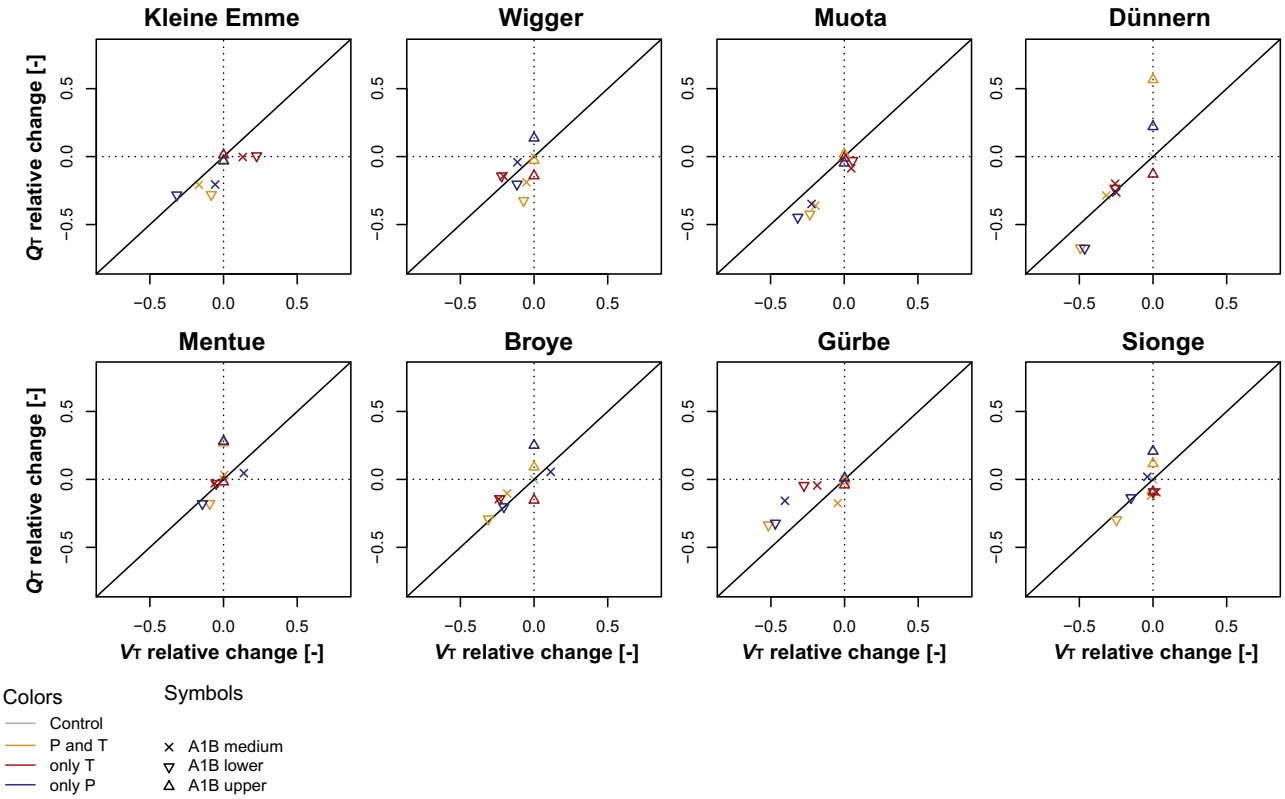


**Fig. 8.** Relative change of the design variable quantiles peak discharge ($Q_T$) and hydrograph volume ($V_T$) compared to the quantiles of the control period for events of a return period of 100 years for the eight study catchments in the regions CHNE (upper panel) and CHW (lower panel). Relative changes are given for the *P* and *T*, the only *P*, and the only *T* scenarios. The scenarios refer to the A1B medium, lower, and upper emission scenario. Points lying on the bold, diagonal line represent proportional changes of peak discharges and hydrograph volumes. Points lying on the dashed lines represent changes of only one variable.

strongly in winter compared to summer (e.g. Wigger, Muota). The proportionality of peak discharge and hydrograph volume was quit high in summer except for Kleine Emme and Gürbe. The points far off the diagonal in the Muota and Sionge catchments resulted from the non-reliability of those estimates due to very small sample sizes when working on a seasonal basis.

## 5. Discussion

### 5.1. Impact of climate change on floods in a bivariate context

Our results demonstrate that peak discharges and hydrograph volumes are not necessarily equally affected by projected climate change and that their dependence is influenced by changes in precipitation and temperature. In addition, they show that hydrograph shapes might also be affected by climate change. While hydrograph volumes are projected to change proportionally to peak discharges in some catchments, they might undergo smaller or stronger changes with respect to peak discharges in other catchments. The disproportion in changes of $Q_T$ and $V_T$ was even more expressed on a seasonal than on an annual scale, which suggests that changes in both design variable quantiles should be analyzed at a seasonal scale in addition to the annual scale. This suggestion is in line with findings of Blöschl et al. (2017) who found that the seasonality of floods has been affected in the last 50 years. It is also in line with findings of Kundzewicz (2002), Köplin et al. (2014), and Vormoor et al. (2015) who stated that the most obvious change of floods will be a seasonal change because the anticipated seasonal shift in precipitation is likely to alter the runoff behavior and flood generation. However, it is rather the seasonal frequency that changes and not necessarily the seasonal magnitude, which was also found by Vormoor et al. (2015). Like our results, their results showed that winter floods will gain in importance compared to summer floods. The increased flows in winter can be explained by higher temperatures, more precipitation, diminishing water storage in snow (Kundzewicz, 2002), and a seasonal shift in the onset of snowmelt. The results obtained in this study indicate that the seasonal changes in flood frequencies seem to be largely attributable to anticipated changes in precipitation since the results of the *P* and *T* scenario and the only *P* scenario are very similar. We illustrate that a bivariate evaluation is useful, even for the very simple case of delta change climate scenarios. We do by no means claim that the simulated changes of peaks and values are real predictions for the future. However, our results still illustrate that the bivariate approach is useful.

### 5.2. Climate impact assessment approach

The application of the approach proposed for the assessment of climate impacts on the bivariate characteristics of floods has shown that the approach is useful for gaining insights into joint changes of peak discharges, hydrograph volumes, and shapes. It offers a new way of looking at climate impacts on floods by constructing synthetic design hydrographs that represent the entire hydrograph shape. We demonstrated that it is important to consider both effects on peak discharges and hydrograph volumes when estimating design events for future climate conditions. Furthermore, we showed that the consideration of flood seasonality is important especially because the season of occurrence of the large floods may be shifted due to projected changes in climate. Therefore, SDHs constructed to represent future climate conditions should rather be constructed at a seasonal instead of an annual scale, to better understand where the expected

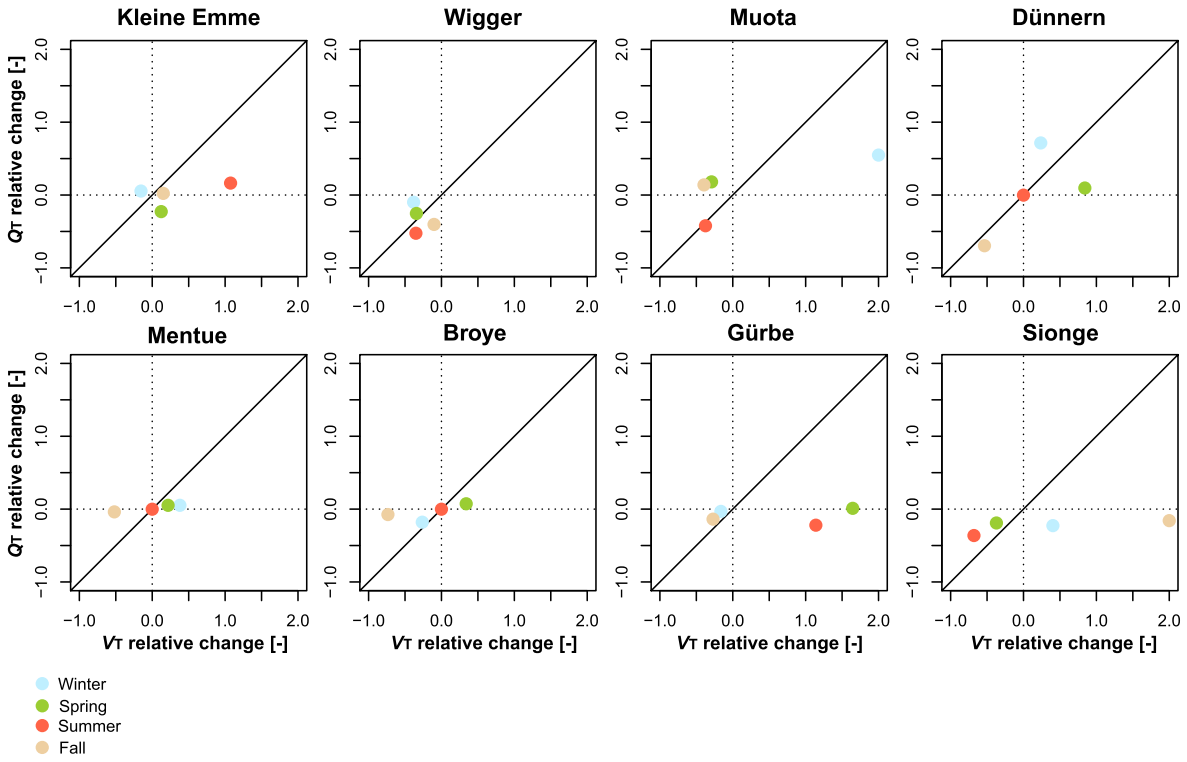


**Fig. 9.** Relative changes in seasonal design variable quantiles peak discharge and hydrograph volume obtained for the *P* and *T* scenario compared to the control run for a return period of $T = 100$ years for the eight study catchments in the regions CHNE (upper panel) and CHW (lower panel). Points lying on the bold, diagonal line represent proportional changes of peak discharges and hydrograph volumes. Points lying on the dashed lines represent changes of only one variable. Outliers were displayed on the border of the *y*-axis (see Muota and Sionge).

changes are coming from. The approach proposed here is directly available for applications to assess climate impacts on SDHs in other catchments and under other projected climate scenarios or to assess the impact of land use changes on floods. It has low computation times and can therefore be used to evaluate many emission scenarios at a very low computational cost.

### 5.3. Uncertainty sources and limitations

Rather than making real predictions of changes, we demonstrate that the joint consideration of peak discharges and hydrograph volumes is important in climate impact assessments. An in depth assessment of future changes is not possible since the approach presented here is affected by several sources of uncertainty (Dobler et al., 2012; Horton, 2005; Kundzewicz et al., 2014; Wilby et al., 2008). These uncertainty sources result in large discrepancies between flood hazard projections over Europe (Kundzewicz et al., 2017). The consideration of the lower and upper bound of the change factors related to the A1B emission scenario and the consideration of three precipitation and temperature scenarios indicate that the uncertainty is substantial and that a clear statement about the magnitude and the direction of changes is not possible. Various other uncertainty sources hamper the possibility to make clear statements about climate impact on floods. These include: emission scenarios (Cameron, 2006; Vormoor et al., 2015), GCMs, RCMs, and downscaling from GCMs to RCMs (Vormoor et al., 2015), the change factor approach, uncertainty in the hydrological model (Cameron, 2006; Cameron et al., 2000), its calibration, and the lack of robustness in hydrological model parameterization for simulations under transient hydro-meteorological conditions (Vormoor et al., 2015), and the bivariate flood frequency and SDH construction model (Brunner et al., 2017a; Dung et al., 2015; Serinaldi, 2013).

The consideration of all the uncertainty sources affecting a climate impact assessment is important if one is interested in making real predictions caused by the effect of climate impacts on floods but becomes much less important if the aim is only demonstrating the applicability of an approach.

### 5.4. Perspectives

So far, the bivariate climate impact assessment approach has been applied in gauged catchments only, where a calibration of the hydrological model based on observations is possible. However, the approach would potentially also be applicable to ungauged catchments if a relationship between catchment characteristics and model parameters could be established (Viviroli et al., 2009).

The approach proposed here has been applied to a set of eight study catchments to highlight the importance of the consideration of bivariate flood frequencies in climate impact assessments and relies on the change factor approach. However, this step in the analysis could be updated by more sophisticated methods that provide data at hourly resolution and thus can better represent changes in spatial rainfall patterns and sequences. Since our method is computationally fast, this updating can be done fast or redone when new emission scenarios become available. A new high-resolution regional climate change ensemble has been established for Europe with a resolution of 12.5 km (Jacob et al., 2014) for the new emission scenarios RCP4.5 and RCP8.5 (Moss et al., 2010). A new data set of climate scenarios will be provided by the CH2018 initiative (Knutti et al., 2014).

## 6. Conclusions

The results obtained from the bivariate climate impact analysis showed that projected climate change leads to changes in the

magnitude and the seasonal occurrence of the most extreme flood events in terms of peak discharges and hydrograph volumes. However, peak discharges and hydrograph volumes might not change proportionally, which implies that their joint consideration is crucial in climate impact assessments on floods. The changes in peak discharges and hydrograph volumes affect design hydrograph construction and therefore estimated design variable quantiles for predefined return periods. The consideration of flood seasonality is very important, since the season of occurrence of large floods might shift due to projected changes in climate. Therefore, SDHs should be constructed at a seasonal rather than at an annual scale. Here, we use the climate scenarios for the illustration of the approach rather than for reliable predictions of future runoff changes as these cannot be predicted without knowing future climate conditions. Still, the results indicate that a bivariate analysis of floods is an important extension for climate change impact studies.

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